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HOW WE TEACH | *Classroom and Laboratory Research Projects*

Impact of cardiovascular embryology animations on short-term learning

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Upson-Taboas CF, Montoya R, O'Loughlin VD. Impact of cardiovascular embryology animations on short-term learning. *Adv Physiol Educ* 43: 55–65, 2019; doi:10.1152/advan.00121.2018.—An understanding of human embryology is essential for students to better understand the subjects of human anatomy and physiology. However, human embryology is a challenging subject for many, since they must learn how anatomic structures and physiological processes develop over a period of time. Embryology texts typically use static, two-dimensional images to illustrate the dynamic three-dimensional developmental processes, making it difficult for a student to understand spatial relationships and sequential steps. To help students conceptualize these series of complex dynamic developmental events that occur over time, two of the authors and a graphic artist developed six web-based cardiovascular embryology animations and housed them on an Indiana University website. This research study examines knowledge gains and user satisfaction of students, faculty, and laypeople around the world who accessed these six website animations. Data collection spanned 6 yr, and pretest/posttest assessments (ranging from 4 to 7 multiple-choice questions each) were used to determine immediate knowledge gains of cardiovascular embryology. The total number of completed pretest/posttest assessments ranged from 555 to 1,449 per animation. The number of correct posttest scores was significantly improved over matched pretest scores (confidence interval range 1.3–3.2, depending on the animation, $P < 0.001$), suggesting the animations are useful for embryology learning (at least in the short term). Demographic and user satisfaction information was gathered with an anonymous survey at the end of each animation. Survey data from all animations indicated participants found the animations easy to use and very effective for their learning. This research highlights the positive impacts of web-based animations on learning complicated events of cardiovascular embryology.

animations; cardiovascular embryology; embryology and human development; human anatomy and physiology; medical education; multimedia instruction

INTRODUCTION

Multimedia Instruction and Animations

The purpose of multimedia instruction is to present words and pictures in ways that foster cognitive processes during learning. The instructional objective must be clear and should describe the intended learning outcome (37, 44). Retention (recall) or transfer (application) tests can be used to measure how much meaningful learning has occurred, based on the learning outcome (37, 44).

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Key elements of multimedia instruction manage the capacity for cognitive processes, known as cognitive load. Cognitive load is determined by how information is presented and how complex the material is. Managing cognitive load in multimedia instruction uses visual and verbal channels (dual-channel theory) to manage intrinsic cognitive load, reduce extraneous cognitive load, and increase germane cognitive load (8, 22, 29, 36, 37, 44, 45, 58, 69, 74, 77).

Intrinsic cognitive load manages the essential processing, which is based on the complexity of the material being presented. The experience of the learner plus the material complexity dictates how much effort the learner must put into learning. This effort involves selecting words and images for further processing, organizing those words and images into a coherent cognitive representation, and integrating them with each other and with previous knowledge (37, 38, 44, 69, 73, 74). Extraneous cognitive load refers to inappropriate material or teaching approaches not required to meet the learning objective. This includes multiple sources of different information or redundant sources of material presented at the same time (36, 48, 69, 73). Germane cognitive load is beneficial cognitive load and refers to the cognitive processes relevant to learning, often attributed to learner motivation and preference. These cognitive processes enhance learning rather than hinder it (69, 73, 74).

Web-based animations, as a form of multimedia instruction, have many positives because they are an efficient way to convey material: they can be used at leisure and can allow for the visualization of processes that may not be captured through other imaging methods (70). Animations can further assist learning of complex spatial structures and concepts (7, 21, 55, 62). However, if a learner does not hold the prior image in short-term memory, the learner can be swamped by the dynamic nature of the animation. It has also been suggested that a learner's spatial ability may affect how useful an animation may be to him/her. Thus the spatial ability and level of the learner must be kept in mind when designing web-based animations (4, 18, 32, 34, 73).

Human Embryology Curriculum

Human embryology (growth and development of the preembryo, embryo, and fetus) is a subdiscipline of anatomy, and a subject that is essential for understanding some of the more complex concepts in human anatomy and human physiology. However, human embryology is very challenging for many, since the learner must conceptualize a series of complex dynamic developmental events that occur over a period of time. These developmental events involve changes in anatomic structures as well as physiological processes.

Since traditional embryology texts typically use static, two-dimensional (2D) images to illustrate the dynamic three-dimensional (3D) developmental processes, it can be difficult for a student to understand the development that took place, or to understand the changes that occurred between static *image A* and *image B* (6, 13, 35). High-quality embryology animations that effectively illustrate these dynamic changes have been suggested to help aid in the understanding of embryological processes (16, 47, 64, 65, 75). Specifically, the animations should reduce the mental leaps students have to make when presented with static textbook images that may skip over complex varying movements, shifting of tissues, or changes in organ structure, shape, and size (6, 8, 36).

Many medical schools recently have undergone curricular reform, and this reform has impacted how embryology is taught. In contrast to the past curricula (where embryology often was a standalone course), embryology now is being incorporated in other multidisciplinary courses, such as courses that combine teaching of the anatomical sciences (gross anatomy, embryology, and histology), or courses that focus on organ systems (e.g., a cardiovascular course that examines the anatomy, embryology, physiology, and pathology of the system) (6, 9–11). In addition, the course hours spent on embryology (in either a standalone course or as part of a larger multidisciplinary course) have steadily declined and remain on average at <20 h for the last 30 yr. The number of programs that have offered an embryology laboratory component have also decreased (6, 10, 11). Thus it is more important than ever that today's embryology learning tools be able to be effectively utilized outside of the classroom and minimize some of the learning challenges inherent in the subject.

Learning Tools for Embryology

Despite the broad-based appeal and utility of embryology animations, no animations for cardiovascular embryology were widely available until the very early 2000s. Since then, some embryology-based animations that have been developed include Simbryo (63), the University of New South Wales' Cardiovascular System Development (19), the Endowment for Human Development's Virtual Human Embryo (VHE) (71), the University of Michigan's Multi-Dimensional Human Embryo (MDHE) (67, 68), and Case Western Reserve University School of Medicine's Embryon (12).

However, these resources have some drawbacks. Simbryo is only available to medical students if they purchase *Langman's Medical Embryology* textbook (63), which was not available until its 9th edition in 2004. Simbryo's cardiovascular embryology animation has three views of the heart that move through developmental changes all at the same time. Because all of the developmental events are occurring at the same time, it is difficult for a user to isolate a specific developmental event (e.g., the development of the interatrial septum), and cognitive overload may occur.

The Cardiovascular System Development site offers many cardiovascular embryology animations embedded into their own pages within the larger context of tutorials. The animations, however, cannot stand alone as learning tools due to their brevity. They must be studied with the rest of the information on the tutorial page to understand the processes shown (19).

The VHE and the MDHE are similar in that they show different Carnegie stages of development and are freely available. The VHE animations do a "fly-through" (pass-through) of different MRI segments from the embryo at the same developmental stage (71). The MDHE animations just show a 3D rotation of the embryo at a particular Carnegie stage (68). Neither site shows dimensional changes over time and would have to be pieced to together by the user to "see" such changes.

Embryon's animations may be manipulated in a 3D aspect while highlighting particular features (such as the eye) during development. Their animations move through time and show how these features change at different Carnegie stages (12). However, neither VHE, MDHE, nor Embryon has a cardiovascular embryology animation. Also, only Embryon has been methodologically assessed for learning embryology, which had a positive impact (14, 15).

In the early 2000s, when there were limited tools available to learn embryology, one of the authors (V.D.O) decided to create her own animations. To that end, two of the authors (V.D.O and R.M.) and a graphic artist at Indiana University worked together to create a series of web-based animations to better illustrate the complex dynamic events of cardiovascular embryology. Six animations are currently on the internet via a link on Indiana University's website for Human Embryology Animations (51). While these animations initially were developed for one author's (V.D.O) gross anatomy class, the animations were distributed widely through the internet, allowing for worldwide user knowledge gain and demographic data to be collected. This paper describes the development of these cardiovascular embryology animations, their use worldwide, and examines the following research questions:

1. Does the use of cardiovascular embryology animations result in knowledge gains of the subject, as evidenced by pretest and posttest comparisons?
2. Do users of the cardiovascular embryology animations perceive these tools to be effective and efficient for them to learn the subject matter?

Based on previous research, it is hypothesized that the animations will have a positive short-term gain in the understanding and learning of cardiovascular embryology, and that these animations will be perceived as effective and useful tools for learning (46, 53, 54). To answer these questions, the authors evaluated both short-term learning comprehension of complex 3D structural changes over time using a comparison of pretest and posttest scores, and participant survey reflections, to further elucidate the usefulness of the animations by assessing what improvements could be made in the future.

MATERIALS AND METHODS

The cardiovascular embryology animations were developed as part of a larger embryology animation project, the Human Embryology Animations website (51, 52). This website is freely available and includes embryology animations for multiple body systems. However, for the purposes of this study, the authors wanted to compare animations that examined aspects of the same body system: the cardiovascular system. Table 1 lists the six specific cardiovascular embryology animations developed and briefly describes each animation.

Table 1. *Cardiovascular embryology animations: animation title, acronym, animation format, and brief description of each animation*

Title	Acronym	Animation Format	Brief Description
Interatrial septum development	IASD	QuickTime	Formation of the interatrial septum, including formation of septum primum, septum secundum, and foramen ovale (8 min).
Division of atrioventricular canal	AVCAN	QuickTime	How superior and inferior endocardial cushions divide the atrioventricular canal into left and right atrioventricular openings. 1, Anterior view (3.5 min); 2, left lateral view (3 min).
Development of aorta, pulmonary trunk and interventricular septum	APTIVS	QuickTime	Development of muscular ventricular septum; shows how the truncus arteriosus is subdivided into an aorta and pulmonary trunk; development of muscular part of ventricular septum (6 min).
Fetal vs. postnatal circulatory system	FETCIRC	Flash	Compares fetal circulatory pattern with the postnatal circulatory pattern; shows embryological origin of postnatal circulatory structures.
Pericardium development	PERICARD	Flash	Development of the pericardium from two pleuropericardial folds; phrenic nerve placement.
Aortic arch vessels	AARCH	Flash	Development of the aortic arch vessels, aortic sac, and descending aorta; individual vessel development.

QuickTime Cardiovascular Embryology Animations

Beginning in 2000, three of the animations were outlined by one of the authors (V.D.O.) and drawn by a graphic artist (1): interatrial septum development (IASD) (2), division of the atrioventricular canal (AVCAN), and (3) development of aorta, pulmonary trunk and interventricular septum (APTIVS) (Table 1). These animations were created using Macromedia's vector drawing application Freehand, version 10.0 (Digital Arts Group of Macromedia, Richardson, TX), as well as Shockwave, version 8.0.205 (Macromedia, San Francisco, CA), to animate the drawings. They were then published using QuickTime, version 4.1 (Apple, Cupertino, CA). This presented the animation as a timeline of frames, which could be controlled by QuickTime's video-like controls (Fig. 1*A*). These include the ability to play and pause, as well as to move through the animation using an indicator on the animation progression timeline.

Macromedia Flash Cardiovascular Embryology Animations

The other three cardiovascular embryology animations were created by two of the authors (R.M. and V.D.O.) using Adobe Illustrator, version 9 (Adobe Systems, San Jose, CA) and Macromedia Flash, version 5 (Macromedia, San Francisco, CA) (4): fetal vs. postnatal circulatory system (FETCIRC) (5), pericardium development (PERICARD), and (6) aortic arch vessels (AARCH) (Table 1). Flash allowed for more interactivity with the animation by allowing the user to click through each step, or he/she can click on a specific step in the process being illustrated (Fig. 1*B*).

Participant Recruitment

This research was approved by Indiana University Institutional Review Board (protocol no. 1009001909). Participants were recruited from 2002 until 2012.

Part of the sample of participants came from the students enrolled in the ANAT A550 Human Gross Anatomy course at Indiana University School of Medicine, Bloomington (~35–40 students yearly). The students included first-year medical students and some graduate students from multiple majors. ANAT A550 incorporates approximately 15 h of embryology, spaced throughout the course, with up to 2 h of instruction on cardiovascular embryology, specifically. Students were asked to participate both in class and via e-mail, encouraging them to review the animations, but assessment of the animations was not included in students' grades, nor were the animations assessed for their effectiveness on students' grades.

The sample size also included participants outside the Indiana University School of Medicine so as to include the general public or anyone interested in learning more about cardiovascular embryology, such as students (undergraduate, graduate, and professional) learning embryology at other institutions, professionals wishing to review basic cardiovascular embryology, and laymen hoping to expand their understanding. Some participants in this group were solicited through various organizations, including American Association of Anatomists,

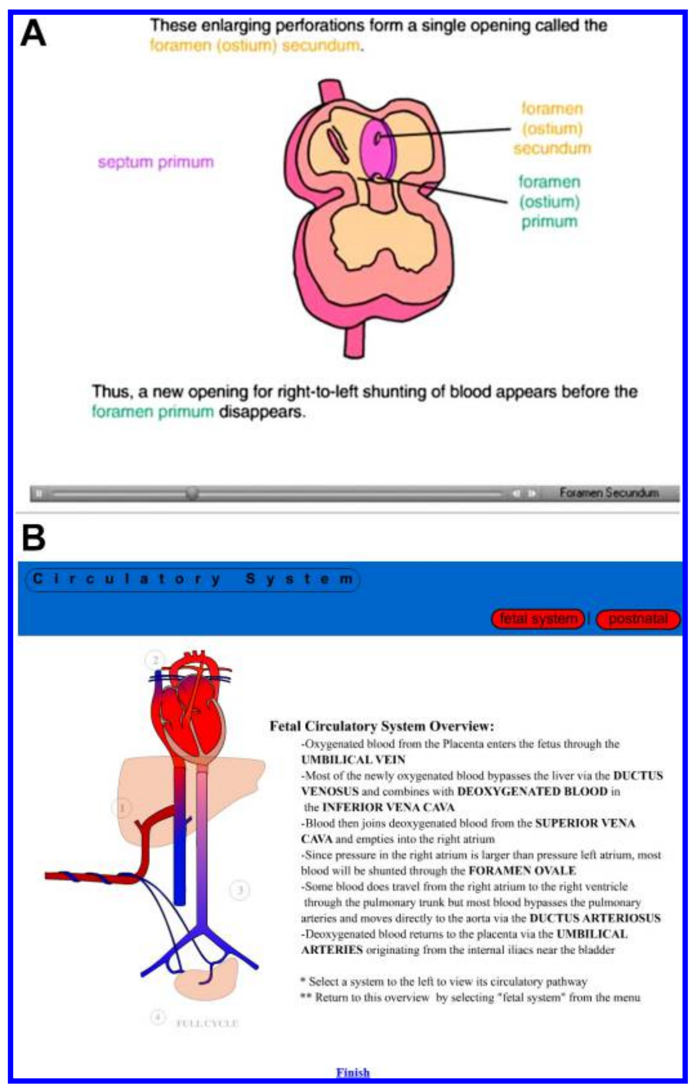

Fig. 1. Comparison of the cardiovascular embryology animation formats. *A*: Quicktime example. *B*: Flash example.

Human Anatomy and Physiology Society, and all educational centers affiliated with Indiana University School of Medicine, as well as through e-mails to students at other universities. Numerous unsolicited participants found the animations through a web-based search and participated in the study as well. The data gathered from all participants (male n = 3,625, female n = 6,803) would allow for the analysis of each animation's educational usefulness for a highly diverse set of participants.

Procedure for Accessing and Reviewing Cardiovascular Animations

The process for participating in the study consisted of a series of steps: *1*) accessing the cardiovascular embryology animation page; *2*) filling out an online consent form; *3*) completing the cardiovascular embryology pretest; *4*) viewing the cardiovascular embryology animation; *5*) completing the cardiovascular embryology posttest; and *6*) submitting the cardiovascular animation assessment survey. Each of these steps is described in detail below.

Cardiovascular embryology animation page. The participant experience started at the cardiovascular embryology animation "splash page," where they chose a hyperlink to the specific animation they wished to view. On clicking the link, a pop-up box would appear asking the participant if they would like to participate in the study, giving "yes" or "no" options. Negative responses moved the participant to a path where they still could participate in the pretest, view the embryology animation, and take the posttest, but none of their answers was collected and stored.

Online consent form. If a participant agreed to participate in the study by clicking "yes," then the participant was directed to an online consent form that detailed the nature of the study and the specific data to be collected. At this stage, the participant was asked again if they would like to participate in the study. The participant could again opt out of the study by choosing "no," at which time they would follow the path described above. A valid e-mail address was required for a "yes" response so participants could be sent a verification e-mail for inclusion in the study. On receiving the e-mail, the participant had the option at any time of replying to the e-mail and requesting to be removed from the study. From this point on, all data from the pretest and posttest were collected.

Cardiovascular embryology pretest. The pretest consisted of approximately four to seven multiple-choice questions (see supplemental material; supplemental data are available in the data supplement online at the *Advances in Physiology Education* website) on various aspects of cardiovascular embryology that would be discussed in the animation. Examples can be seen in Fig. 2. A separate, extra question on the pretest only asked the viewer how many times he/she had viewed the animation. This extra question allowed for the removal of any individual who had seen the animation before, which could thus potentially impact pretest scores.

Example Pretest Questions

1. Which statement is **TRUE** about the prenatal heart?
    a. In the developing fetus, blood is shunted from the left atrium to the right atrium.
    b. The fetus has greater pulmonary arterial pressure than the newborn.
    c. The interatrial septum forms a solid, fused wall between left and right atrium by 8 weeks of development.
    d. The prenatal left atrium is the first heart chamber to receive oxygenated blood.
    e. Don't know
2. Oxygenated blood travels from the placenta to the fetus through the:
    a. Umbilical vein
    b. Umbilical artery
    c. Aorta
    d. Ductus arteriosus
    e. Don't know
3. What anatomic structure is located within, and migrates with, each pleuropericardial fold?
    a. Lung bud
    b. Phrenic nerve
    c. Vagus nerve
    d. Parietal pleura
    e. Don't know

Fig. 2. Examples of pretest questions. *Question 1* is from interatrial septum development, *question 2* is from fetal vs. postnatal circulatory system, and *question 3* is from pericardium development.

The multiple-choice questions were modeled after questions from previous Indiana University School of Medicine–Bloomington ANAT A550 examinations from before 2000 that had already been analyzed for reliability. Each question had five responses, with the last answer being "I don't know." The participant was instructed not to guess, and only one answer per question was allowed. The default answer for each question was set to "I don't know", again to discourage guessing. If the participant had consented to participate, they were then asked to verify their e-mail address before submitting the pretest. Answers were then recorded in a database, and the e-mail address served as an identifier for the person's answers. This allowed the authors to identify duplicate tests to remove the duplicates and keep only the first pair of tests. After submission, the participant's answers were shown, but the correct answers were not.

Viewing the cardiovascular embryology animation. After submitting the pretest, participants were taken to the animation page. Participants were allowed to take as much time as they needed to view the animation and for as many times as they felt necessary. Once they had completed their viewing, a "Finish" link brought them to the posttest assessment.

Cardiovascular embryology posttest. The cardiovascular embryology posttest was set up in a similar manner to the pretest. The same questions were again presented in a multiple-choice format with the participant selecting his/her answer with the default answer set to "I don't know." Each question and answer set was the same as in the pretest, so pretest and posttest answers could be directly compared. The only question that was not on the posttest (and just on the pretest) was the extra question about how many times the participant had viewed the animation. After all the fields were completed and the participant submitted his/her answers, the participant was taken to an answer page similar to the pretest answer page. Along with displaying the participant's answer, this time the correct answers for each question were also displayed.

Cardiovascular embryology animation assessment survey. At the end of each animation was an animation assessment survey, so users could provide anonymous demographic data and provide feedback about the specific animation. The assessment survey used the same questions for all of the animations and contained 12 short questions along with comment boxes. Likert-scale questions allowed a participant to rate each animation's effectiveness in learning the material, ease of use, and effectiveness of learning (if the animations aided in answering questions and if the topic was adequately assessed by the posttest questions). Other information collected included demographics, such as age range, profession, sex, and location, as well as information on the participant's purpose of use and how he/she learned about the animations. A final open-ended comment box was also provided to explain any comments, errors, or suggestions on how we could improve the animations. The assessment survey was open to all individuals, regardless of whether they also agreed to have their pretest and posttest data collected.

Statistical and Qualitative Analyses

Data were collected from 2002 until 2012 using the database software FileMaker Pro, version 6.0 (FileMaker, Santa Clara, CA). The first year (2002) of the AARCH animation data, and the data from all animations from years 2009–2012 were corrupted, restricting data analysis to data from 2003 to 2008 for the AARCH data and from 2002 to 2008 for the other animations. Entries were deemed invalid if a pretest and posttest could not be matched, a legitimate e-mail was not used, or there were duplicate entries. Invalid entries were removed from the database.

The number of correct answers was tabulated for each participant's pretest and posttest, which were then compared using paired Student's

Table 2. *Pretest/posttest and survey comparisons for each cardiovascular embryology animation*

	Consented to Participate*, *n*	Pretests/Posttests, no.	Questions, no.	Mean Score Pretest (SD)	Mean Score Posttest (SD)	*P* Value	95% CI	*t*	Cohen's *d*	Assessment Surveys†, no.	Open-Ended Responses, no.
AARCH	8,251	610	5	1.6 (1.5)	3.3 (1.6)	<0.001	1.6–1.9	25.4	1.1	966	126
FETCIRC	9,438	923	5	2.6 (1.8)	4.0 (1.3)	<0.001	1.3–1.6	24.4	0.9	4,451	436
PERICARD	4,998	503	4	0.5 (0.9)	2.5 (1.2)	<0.001	1.8–2.1	33.8	1.9	555	87
APTIVS	10,355	837	5	1.4 (1.3)	3.1 (1.5)	<0.001	1.6–1.8	32.0	1.2	1,382	137
AVCAN	8,266	807	4	0.6 (0.9)	2.9 (1.3)	<0.001	2.2–2.4	43.5	2.0	1,487	139
IASD	15,824	1,286	7	2.0 (2.0)	5.1 (2.0)	<0.001	2.9–3.2	47.3	1.5	2,481	275

n, No. of participants. AARCH, aortic arch vessels; APTIVS, development of aorta, pulmonary trunk and interventricular septum; AVCAN, division of the atrioventricular canal; FETCIRC, fetal vs. postnatal circulatory system; IASD, interatrial septum development; PERICARD, pericardium development. *Although many people initially agreed to participate in the study, not everyone completed both a pretest and a posttest. The reasons for this high attrition included user issues with running the animation on their computer, or simply not completing a posttest. †Surveys were anonymous and could not be matched with pretest and posttest responses. Not all surveys were completed in their entirety but were included if any questions were answered.

t-tests in the statistical software program STATA, version 15.0 (StataCorp LLC 2017). Cohen's *d* values were determined to measure the effect size of each animation. A common reference for effect size is small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$), where effect size may be interpreted as a change in standard deviation (29). Because the authors were not comparing the animations' effectiveness to the effectiveness of other resources, no further statistical analysis was performed.

Additional analyses were conducted using the assessment survey data. Demographic data were quantified, whereas qualitative analysis was done for participant perceptions of the animations. Any survey that returned null answers for the entire survey was removed from analysis. A thematic analysis of the qualitative data was performed using a grounded theory approach (1, 3, 28). Responses from the final open-ended question in each survey, "Please explain any comments, errors, or suggestions on how we can improve this animation," were first transcribed into single phrases, single sentences, or small groups of phrases or sentences, which provided discrete sections for analysis. These discrete sections were then coded into three primary themes: generally positive comments, generally negative comments, and suggestions for improvement. Secondary theme codes were then created for each primary theme. One author (C.U.) initially generated the coding scheme, and, in consultation with another author (V.D.O) versed in grounded theory, the codes were discussed, modified, and revised. The final secondary theme codes were then coded for presence or absence by C.U. The final coding scheme is as follow: generally positive comments were coded for nonspecific affective comments, comments that mentioned some version of "help" (helped, helpful, etc.), and miscellaneous positive comments; generally negative comments were coded for perceived errors with the animations or posttest questions, nonspecific negative comments, and technical issues with the animations; and suggestions for improvement were coded for technical changes to the animations/tests/surveys, additions to or requests for more animations, and changes to pretest/posttest questions.

RESULTS

Numbers of Participants in the Study

Table 2 lists the number of people who consented to participate, the number of completed pretests and posttests received, and the number of assessment surveys completed, along with the number of final open-ended responses. IASD had the greatest number of people who consented to participate (15,824), whereas PERICARD had the least (4,998). Unfortunately, although an individual may have consented to participate in the study, only 7–10% of participants completed both the pretests and posttests (range of $n = 503$ for PERICARD to $n = 1,286$ for IASD). Not all of the surveys were completed in their entirety, but surveys were included in the analysis if one or more questions were completed. The number of completed assessment surveys varied by animation, ranging from 555 (PERICARD) to 4,451 (FETCIRC). Final open-ended responses for thematic analysis came from only 9–16% of the included surveys (range of $n = 87$ for PERICARD to $n = 436$ FETCIRC) (Table 2).

Pretest/Posttest Comparisons

Table 2 also shows the mean pretest scores compared with the mean posttest scores. Participant posttest scores were statistically significantly higher than matched pretest scores, ranging from 14 to 51% of correct answers on pretests (average 28%), and 62–80% on posttests (average 69%) (confidence interval range 1.3–3.2, depending on the animation; $P < 0.001$ regardless of the animation) (Fig. 3). The effect sizes (*d*) for all of the animations were large, ranging from 0.91 to 2.00, suggesting that the animations improved short-term learning by 1–2 SDs, depending on the animation.

Animation Assessment Surveys

Animation assessment surveys were anonymous and could be completed by both participants and nonparticipants. Those who filled out the animation survey, on average, visited once (81%), but may have visited multiple times. Survey participants were mostly medical students (60%), female (65%), and between the ages of 18–25 yr (51%). Participants were directed to the animations primarily by an instructor (34%), peer (29%), or by internet search (28%). Most were from the United States (72%), although there were respondents from virtually all continents.

In general, participants found all of the animations very easy to use (83%) and very effective for learning the material (74%). The animations were overwhelmingly found to aid in answering posttest questions (94%), and the posttest questions were found to be adequate for assessing what was learned (92%).

Thematic Analysis of Survey Data

Table 2 shows the total number of surveys completed and the number of open-ended responses from the last survey question after each animation as well. Many participants offered multiple types of comments, with a total of $n = 1,419$ analyzed comments from 1,200 open-ended responses. The three major themes analyzed were generally positive comments

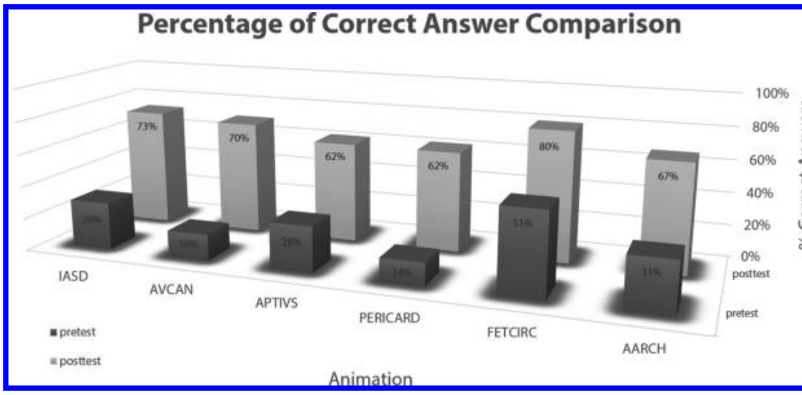

Fig. 3. Comparison of percentage of correct answers on pretests vs. matched posttests. AARCH, aortic arch vessels; APTIVS, development of aorta, pulmonary trunk and interventricular septum; AVCAN, division of the atrioventricular canal; FETCIRC, fetal vs. postnatal circulatory system; IASD, interatrial septum development; PERICARD, pericardium development.

(48%, n = 577), generally negative comments (18%, n = 217), and suggestions for improvement (52%, n = 625). Specific examples of comments for each theme can be seen in Table 3. General positive comments were coded for nonspecific affective comments (75%, n = 433), comments that mentioned some version of "help" (helped, helpful, etc.) (22%, n = 127), and miscellaneous positive comments (3%, n = 17). The nonspecific affective comments included such comments as "Thank you!", "Awesome!", "Great Animations!", and comments about marketing to textbooks or as online teaching tools. Comments that mentioned some version of "help" included how the animations helped people study, helped with visualizing the processes occurring, or helped with understanding a difficult topic. Other miscellaneous positive comments included how the animations were better than a textbook or instructor, as well as how they liked specific aspects of the animations, such the interactivity of the animation or the ability to control the speed of the animation.

Table 3. *Thematic analysis: specific examples of final open-ended responses.*

Theme	Comment
	General positive
Nonspecific affective	• "Beautiful and succinct." "Great animation." "Great resource." "Thanks, excellent stuff." "Wonderful site." "Great job, keep it up." • "This is absolutely superb. I have told all my colleagues about this invaluable resource. Many thanks." • "I am writing a book chapter on pediatric cardiology. I have a short paragraph on embryology and will include this site as a reference. Thanks for your work on this."
Mentioned some version of "help"	• "The animation was very well presented, hence [it] enabled me to further improve my understanding of the heart/physiology." • "I normally hate embryology, but this really helps me actually visualize what's going on." • "This was a really great resource It helps to understand what is actually going on and see it, instead of just memorizing structures."
Miscellaneous positive comments	• "Thanks very much. Very useful animation/description of what is a dynamic process (so much harder in dry textbooks of embryology)." • "These animations are as perfect as I have encountered ANYWHERE. Special strengths are the gradual stepwise nature of the animations (not too much attempted at once). Second, each step is labeled perfectly: not too much, not too little. Third, the animations are simple (not too busy) and run at a nice speed (easy to follow)."
	General negative
Perceived errors	• There are a few minor errors in the posttest questions, and the answers that go along with them." • "The correct answer for *questions 3* and *4* give a correct answer that is not one of the choices on the posttest."
Nonspecific	• "I really do love these animations, they are extremely helpful. . . . this one just stuck out as the most unclear and least helpful of the group." • "I have viewed these videos a number of times. It seems silly for me to continue to fill out these surveys each time."
Technical issues	• "The animations I can see have all been great, but it annoys me that I can't see the ones in QuickTime, although I downloaded QuickTime, even though I already have it on my PC."
	Suggestions for improvement
Technical changes	• "The week number at which things happen could be in bold, as this is the hardest thing to remember from the animation. Also, it went quite slowly; maybe speed could be controlled by viewer?" • "Since I am giving my e-mail, maybe use cookies so I don't have to give my age and gender and other nonchanging things each time."
Additions	• "Go into pathology of the heart, congenital abnormalities, murmurs, septal defects, tetralogy of fallow, etc." • "The fetal and postnatal circulation teaching tool is very useful. It is good to have a visual aid like this. Could you develop one similar to explain the fetal lungs in utero and postbirth?" • "Do more on other physiological pathways . . . perhaps hormone pathways as well."
Pretest/posttest questions	• "We should have more time to review the answers before automatically switching to the survey." • "I think there should be more levels of testing, like more detailed questions or harder questions for those who need to know more information for their course."

Comments have been edited only for clarification.

General negative comments were coded for perceived errors with the animations or posttest questions (58%, n = 125), nonspecific negative comments (21%, n = 46), and technical issues with the animations (21%, n = 46). Errors with the animations or posttest questions included incorrect or confusing information in the animation or in a posttest answer. Nonspecific negative comments included conflicting information from what they knew, the surveys took too much time, or there was too much information, which made the animation hard to follow, vague, or not helpful. Technical issues with the animations were predominantly issues with the animations not working for the participant due to format incompatibility with the participant's browser.

Suggestions for improvement were coded for technical changes to the animations, tests, or surveys (50%, n = 313), additions to the animations or requests for more animations (40%, n = 250), and changes to the pretest/posttest questions (10%, n = 62). Technical changes to the animations included adding labels, audio, a timeline for concurrent events, or adding more views, such as 3D. They also included requests for the ability to change the speed or size of the animations, and to print, share, or download the animations. Participants also wanted the ability to skip surveys by implementing an overall survey for all animations that was answered once or by adding a clickable button to be able to skip the surveys. Additions to the animations included adding pathological conditions, congenital defects, or clinical applications, and requests for more animations included other systems, such as lung development or gastrointestinal embryology. Changes to the questions included adding more questions in general or adding more complex posttest questions.

DISCUSSION

The goal of this research was to examine if the cardiovascular embryology animations examined in this study resulted in knowledge gains of the subject. The cardiovascular embryology animations were shown to be effective for short-term learning based on improved posttest scores, since the average number of correct answers increased from 28% on pretests to 69% on posttests. The confidence intervals suggest that the minimum improvement from the pretests to the posttests was an increase in 1.3 correct questions for FETCIRC, with a maximum improvement of 3.2 correct questions for IASD. These improvements support the first hypothesis that the animations will have a positive impact on learning cardiovascular embryology. The number of animation assessment surveys completed ranged from 555 to 4,451 and showed that the animations were well received, and that they were found to be easy to use and effective for learning, supporting the second hypothesis. Of the assessment surveys, 1,200 open-ended responses underwent thematic analysis and were largely generally positive or suggestions for improvement.

Embryology and Multimedia Principles

Recent research by Cassidy (6) has found that, while embryology is not a major focus of medical education, surveyed medical faculty agree that embryology is important and should be included in the curriculum. These faculty further agreed that embryology helps prepare students for understanding adult anatomy, and we argue that embryology knowledge also is essential for understanding selected pathophysiological concepts as well. Cassidy's survey respondents (6) stated that students should be taught with clinical applications in mind so that they understand the rationale for what organs and organ systems on which to concentrate. To do this, faculty and students explicitly recommended the development of supplemental high-quality animations as a suggestion for the improvement of embryology curriculum (6). Cassidy's 2016 survey and interview findings suggest that there continues to be a need for embryology animations.

However, animations may not be helpful if they do not incorporate key elements of multimedia instruction (2). The principles of multimedia instruction were developed to manage cognitive load and have evolved over the years (39–41, 48, 49). In the early 2000s, only a select number of principles had been developed: modality for managing intrinsic cognitive load; coherence, contiguity, and redundancy for reducing extraneous cognitive load; and interactivity for increasing germane cognitive load. Modality expands the basic idea of multimedia instruction of using words and pictures together and refers to words presented as auditory narration rather than visual on-screen text (48). Coherence refers to the elimination of extra sounds, such as sound effects or music that are not necessary for learning (49). Contiguity refers to words and pictures presented close to each other in time and space (39, 48). Redundancy refers to the elimination of on-screen text that duplicates words being spoken in the narration (41). Interactivity refers to the basic ability to control the rate of the presentation, such as clicking a button to continue (40). Some of these principles have been further described or clarified and have become better guidelines for managing cognitive load.

Managing intrinsic cognitive load uses the modality principle, which has not changed, but has expanded to include pretraining. Pretraining is used to define key terms at the beginning of the animation (38, 43, 77). Reducing extraneous cognitive load uses expanded coherence and contiguity principles, and the redundancy principle, which is unchanged, but now also includes the signaling principle. Coherence has been clarified to include eliminating unnecessary visual information, as well as unnecessary sound (38, 73, 77). Contiguity has been expanded to include temporal and spatial contiguity: temporal contiguity refers to narrations matching the timing of visual elements in the animation, and spatial contiguity refers to labels appearing next to their corresponding graphics. Signaling suggests highlighting essential material in some way (38, 73, 77). The interactivity principle, which increases germane cognitive load, has been expanded from simply controlling the rate of the presentation to giving the user control over the order and speed of the animation, as well as the ability to manipulate the view by rotation or zoom in/out (17, 61, 77).

Do These Cardiovascular Animations Abide by Multimedia Instruction Principles?

The animations in this research were developed in the early 2000s and did not intentionally follow any particular elements of multimedia instruction. However, these cardiovascular embryology animations still follow several of the expanded multimedia principles.

To manage intrinsic cognitive load, all of the cardiovascular embryology animations use words and images, but only the

IASD and AVCAN animations use narration, as per the modality principle. None of the QuickTime animations use the pretraining principle. Conversely, although the Flash animations do not provide definitions, they do provide a list of key words and descriptions of actions before each animation as a type of pretraining.

To reduce extraneous cognitive load, all of the animations use the coherence principle with no unnecessary verbal or visual information. All of the animations use spatial contiguity well, with the labels appearing close to the structures being highlighted. The IASD and AVCAN animations use the temporal contiguity principle by matching the narration timing with the visual elements. This may have contributed to IASD and AVCAN having the largest increases in mean scores from pretest to posttest (3.1 and 2.3 points, respectively). However, the temporal contiguity principle is not applicable to the other animations due to the lack of narration. IASD and AVCAN do have redundant narration with some blocks of on-screen text, but not all of the narration is presented with written text. None of the other animations has a verbal component, making the redundancy principal inapplicable. All of the animations use the signaling principle, highlighting essential material when appropriate. The animations also include color coding of terms in the text, with the labels by the graphic.

To increase germane cognitive load, all of the animations have some aspect of interactivity. The QuickTime animations have the ability to stop, start, and pause the animation, as well as move the progression cursor forward or backward to any part of the animation. The Flash animations are clickable animations, where the user can click on any part of the animation at any time to see that particular portion. None of the animations has the ability to change the speed or the ability to manipulate the view of the animation. But the ability to start, pause, and stop the animations allows the participants to stop and reflect on what they were learning as they progress, as well as makes an allowance for the spatial ability and learning level of the user (4, 18, 32, 34, 73).

Suggestions for Improving the Animations

Many of the suggestions for improvement from the animation survey responses address some of the multimedia principle issues discussed above. Adding narration, even when on-screen text was present, was requested 8% of the time (102/1,200 responses). This would address the need for narration to meet the modality principle for the animations that do not have narration, but would conflict with the redundancy principle for animations with on-screen text. However, adding narration with on-screen text could accommodate for multiple styles of learning, as well as disabilities, such as hearing and visual impairment (27, 41). Redundancy has been shown to be effective when minimized to short, two- to three-word phrases that emphasize the point being narrated, especially when an aspect of narration or on-screen text may overload the verbal or visual channels (41, 42, 77).

One suggestion for improvement that was not requested in the assessment surveys was adding definitions to the beginning of animations, or, at the very least, adding overviews of terms to the QuickTime animations to be consistent with the Flash animations, which would fulfill the pretraining principle. The assessment surveys did offer a suggestion for adding a timeline for concurrent events during development, which would enhance temporal contiguity. If the timeline were interactive, whereby a user could click on specific days of development to see the multiple events occurring at that time, this would add to the interactivity of the animations as well. Another request from the surveys related to interactivity were to have the ability to speed up or slow down the animations, such as having a clickable button to run the speed at 0.5× to 2×. An additional request was to add more views of the structures discussed and to have the ability to manipulate the view, either by zooming in or out or via 3D manipulation. This task would require the animation format to be changed and/or updated, which could be worth the gains, since manipulable 3D animations have been shown to improve knowledge gains more than 2D animations (20, 76).

However, there are many challenges in keeping animations up to date with the ever-changing operating systems and software updates. Some of the computer issues identified in the assessment surveys are very likely related to difficulty in viewing the animations because of the plug-ins required for the animation format. Recently, support for Flash is in the process of being phased out, as browsers, such as Chrome and Safari, move to support HTML5 due to security reasons, making the Flash animations inaccessible on mobile devices and more recent Apple computers (50, 56, 72). The Firefox browser has not completely removed Flash, but moved to a "click-to-activate" format in 2017 (66). Flash is still a reliable platform, even with the security issues, but it is being surpassed by HTML5 (50). QuickTime still works for most computers, but, also due to security reasons, Apple has discontinued support for QuickTime on Windows (57). Subsequently, it too is being put aside by Safari in preference for HTML5 (72). Fortunately, the QuickTime animations are currently available on mobile devices, regardless of the browser platform. At this time, all of the animations work best on Windows computers with the Firefox browser. However, a future direction may be to redevelop or merge the current animations into new animation formats using HTML5 or formats that can be used with YouTube to keep up with ever-changing media technology, since YouTube has the same animation controls as QuickTime and has been found to be an effective tool in anatomy and physiology education (23).

Final suggestions for improving the animations were to make the animations downloadable or printable. The animations initially did not have these options available, but, due to browser updates, the IASD and AVCAN animations may automatically download, and APTIVS has a link for downloading, depending on the browser and the computer. Downloading any of the Flash animations is not currently an option, but could be added. Printability could be added to all of the animations as well, but, until then, there are now technological options for taking screen shots that could be incorporated into printable documents.

Limitations

A major limitation of this research is the age of the data, since these cardiovascular embryology animations were developed in the early 2000s. However, although the data are older and because the data do show short-term knowledge gains, it still provides a wealth of information that is useful. This information could be used to modernize the animations and bring them up to date to more recent formats for animation development.

One other limitation of this research is that it tested only short-term learning in the form of immediate memory retrieval. This research was designed to evaluate whether short-term learning occurred and to assess the receptiveness of the animations through surveys. It was not designed to compare methods, types of animations, or to measure the animations' effect on long-term learning, leading to the lack of a control group.

Another limitation is testing bias since the posttest questions were seen previously in the pretests. Research has shown that taking a test on material may have a positive effect on future retention, more so than spending time on studying the material, a situation called the "testing effect" (31, 59, 60). Testing requires retrieval of material from memory, leading to better memory. This may have allowed recall on the posttest from the pretest, because repeated testing is an effective strategy for learning and retaining information (33). Although this research was not designed to test long-term memory retention, repeated retrieval practice has been well studied and is shown to increase long-term memory learning (24–26, 59). The long-term effect of the testing effect has even been shown to affect the ability to recall information after >6 mo (5, 60).

Because Institutional Review Board requirements resulted in having a "no consent" way of viewing the animations, our numbers for participation were lower than what was desired. Attrition was a considerable limitation because of this and may have been due to technical issues the participant had with running the actual animation (we gathered this data from the assessment surveys and from e-mails to one of the authors when an individual contacted that author for computer help). More participants completed the survey (20%) than the pretest/posttest (9%), but the surveys were completely anonymous, and duplicate surveys could not be identified for deletion, whereas duplicate pretests/posttests were deleted. Another possible contribution to attrition may have been participant fatigue as they went through each step of the process.

Conclusions

Knowledge of human embryology may facilitate a better understanding of adult anatomy and physiological processes, as well as potential pathophysiological events. As human embryology is a challenging subject, there is a strong need for learning tools that help reduce extraneous cognitive load and facilitate germane cognitive load when learning this subject. The present study showed that web-based animations were effective tools for short-term learning of cardiovascular embryology. These animations were perceived as effective for learning and were received very well by users. This research supports the use of multimedia principles when designing animations and successfully demonstrated the benefits of animations in learning complex spatial structures and concepts. Keeping in mind technological challenges and suggestions for improvement, further development of these animations may lead to future research to evaluate their effectiveness for long-term learning.

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AUTHOR CONTRIBUTIONS

C.F.U.-T., R.M., and V.D.O. analyzed data; C.F.U.-T., R.M., and V.D.O. interpreted results of experiments; C.F.U.-T. prepared figures; C.F.U.-T. drafted manuscript; C.F.U.-T. and V.D.O. edited and revised manuscript; C.F.U.-T. and V.D.O. approved final version of manuscript; R.M. and V.D.O. performed experiments.

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